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DRILLING FLUIDS AND LOST CIRCULATION IN HOT DRY ROCK GEOTHERMAL WELLS AT FENTON HILL

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ABSTRACT

Geothermal hot dry rock drilling activities at Fenton Hill in the Jemez Mountains of northern New Mexico encountered problems in designing drilling fluids that will reduce catastrophic lost circulation. Four wells (GT-2, EE-1, EE-2, and EE-3) penetrated 733 m (2405 ft) of Cenozoic and Paleozoic sediments and Precambrian crystalline rock units to +4572 m (+15,000 ft). The Cenozoic rocks consist of volcanics (rhyolite, tuff, and pumice) and volcaniclastic sediments. Paleozoic strata include Permian red beds (Abo Formation) and the Pennsylvanian Madera and Sandia Formations, which consist of massive limestones and shales. Beneath the Sandia Formation are igneous and metamorphic rocks of Precambrian age.

The drilling fluid used for the upper sedimentary formations was a polymeric flocculated bentonite drilling fluid. Severe loss of circulation occurred in the cavernous portions of the Sandia limestones. The resultant loss of hydrostatic head caused sloughing of the Abo and of some beds within the Madera Formation. Stuck pipe, repetitive reaming, poor casing cement jobs and costly damage to the intermediate casing resulted.

The Precambrian crystalline portion of the EE-2 and EE-3 wells were directionally drilled at a high angle, and drilled with water as the primary circulating fluid. Due to high temperatures [approximately 320°C (608°F) BHT] and extreme abrasiveness of the deeper part of the Precambrian crystalline rocks, special problems of corrosion inhibition and of torque friction were incurred.

Several techniques were attempted to solve these problems but have met with varying degrees of success. Use of large quantities of fibrous materials (25% to 35% by volume) and of various cements (up to 5000 sacks per well) consistently failed to seal the cavernous zones of the Sandia Formation. Dry drilling as a last resort (drilling without returns) has been performed on all four holes through these cavernous zones. Failure to seal these zones resulted in inadequate hole stabilization and casing damage during placement. Corrosion inhibition while drilling with clear water was complicated by high temperatures which necessitated the circulation of large volumes (15,000 bbls) of water to provide adequate cooling. Massive quantities of an oxygen scavenger (NH_4HSO_3) and the maintenance of a high pH (9.5-11) successfully controlled corrosion. High drill string torque (up to string make-up values) and drag (70% over drill string weight) caused severe loads on the drill string, surface equipment, and casing, and also reduced penetration rates. Several methods of lubrication were tested. The best was a biodegradable lubricant mixture of modified triglycerides and alcohols. Elevated temperatures >191°C (>375°F) caused rapid decline in lubricant efficiency. Therefore the lubricant in the drilling fluid has to be constantly replenished.

An alternate method for drilling the upper sedimentary formations is to use cable tools. Although this does not alleviate the dual problems of hole sloughing and lost circulation, it allows casing to be set as the hole is bored. Although slower, the cable tool approach may be less costly.

DISCLAIMER

BRIEF HISTORY OF THE HDR PROGRAM

During the past ten years several factors have combined to make accepted solutions to the energy problem of the United States more, rather than less controversial. Among these factors are:

- Continuing difficulties in siting and constructing nuclear power plants.
- A growing concern about the environmental and social consequences of mining, transporting, and burning coal.
- Increasing costs and uncertainties about the availability of foreign petroleum.
- Continuous and rapid depletion in domestic reserves of natural gas.

One result is a greater concentration on development of the nearly inexhaustible alternative energy sources. One of these is hot dry rock (HDR) geothermal energy.

"Hot dry rock" energy is defined as the energy latent in naturally occurring dry, but hot, unmelted rock in the earth's crust. It does not produce commercially economic natural steam or hot water because it is dry. Water must be supplied if commercial steam is produced. At varying depths, hot dry rock is everywhere beneath the earth's surface. Even where temperatures of commercially reachable depths are not high enough for generating electricity, the lower temperature HDR potentially might be valuable for space heating, agriculture, and food or chemical processing. Current estimates indicate that beneath the land surface of the United States at depths less than 10 km (6.2 miles), the hot dry rock resource base contains approximately 32 million quads of energy,* with greater than 40% (approximately 13 million quads) at temperatures above 302°F (150°C). It has been calculated that if 2% of this vast resource base could be exploited economically, it would supply the entire country's non-transportation energy needs at the present rate of consumption (1980) for more than 2,000 years.

Recognizing the magnitude of the HDR resource, and that its successful exploitation might involve only inovative modifications of existing equipment and engineering methods, the Los Alamos National Laboratory (formerly the Los Alamos Scientific Laboratory) initiated in 1970 a feasibility study of an underground heat-extraction system in low-permeability hot rock. The concept was to use using conventional hydraulic fracturing techniques to produce a flow connection between two holes drilled into HDR, and then to circulate surface water through the fractures. Study of this concept was continued through FY71, and in FY72 under the U.S. Atomic Energy Commission

* 1 quad of energy = 1 quadrillion (10^{15}) Btu ≈ 334 MW-centuries ≈ 10^{18} J.

(AEC) sponsorship, a search was begun for a nearby location suitable for initial experiments to prove the concept.

An appropriate site was found on the Jemez Plateau approximately 30 km (18.6 miles) west of Los Alamos in Barley Canyon near Fenton Hill (Fig. 1). A slim exploratory hole (GT-1) penetrated approximately 143 m (469 ft) of Precambrian igneous and metamorphic complex rock, and the bottomhole temperature achieved was 100.4°C (212°F). In FY73 concept studies indicated that hydraulic fractures could be created in the Precambrian basement complex rock at moderate pumping pressures, and that the permeability of the rock was sufficiently low to contain a pressurized-water heat-extraction loop. Accordingly, during FY74 and FY75 a second, deeper exploratory hole (GT-2B) was drilled at Fenton Hill approximately 2.5 km (1.6 miles) south of GT-1. This location was considered more suitable for development of a large experimental HDR system. The new hole reached a total depth of 2932 m (9619 ft) and a bottom-hole temperature of 197°C (386°F). A long series of hydraulic-fracturing and pressurization tests confirmed the feasibility of fracturing the basement complex rock at moderate pumping pressures and the ability of the fracture system to hold pressurized water without excessive loss.

In FY75 and FY76, under sponsorship of the Energy Research and Development Administration (ERDA), a second hole (EE-1) was directionally drilled to intersect the largest of the hydraulic fractures initiated from the first hole. The second wellbore reached a total depth of 3064 m (10,053 ft) and achieved a BHT of 205°C (400°F). It did not intersect the fractures, but by fracturing again from EE-1, a high-impedance flow connection was established between the two wellbores.

Design and development of a new and larger heat-extraction system, the Phase II system, at Fenton Hill was started in FY79. Its primary objectives were: (1) seek a minimum bottom-hole rock temperature of 250°C (482°F), (2) develop thermal power of 20 MW or greater, and (3) confirm a thermal drawdown not to exceed 20% in 10 years of continuous operation. The Phase II system is comprised of two new deep holes (EE-2 and EE-3) directionally drilled so that they could be connected together by multiple planar fractures providing a total heat-transfer surface of at least 5,000,000 m^2. Drilling of EE-2 began in April, 1979 and was completed in late May, 1980. Total depth of EE-2 was 4642 m (15,230 ft) with a static bottom-hole temperature of approximately 320°C (608°F). Drilling of EE-3 commenced in late May 1980 and is currently in progress.*

Formal establishment by the U.S. Department of Energy (DOE) of a nationwide Hot Dry Rock Geothermal Energy Development Program (HDR Program) occurred in FY79, and has resulted in a signficant broadening of HDR activities in the United States. The Los Alamos National Laboratory's Fenton Hill Project is the primary center for developing methods, equipment, and instrumentation for creating and

*At the time of printing, the EE-3 well was at 10,528 ft. Its planned total depth is 14,500 ft.

utilizing HDR geothermal reservoirs. The stated objective of this broad HDR Program is:

> "...to determine the potential of hot dry rock geothermal energy as a significant alternate energy source and to provide for its timely development, if warranted."

STRATIGRAPHY

The Fenton Hill project area lies just to the west of the Valles Caldera. The center of this 19 km (12 mile) wide caldera is a distance of about eight miles east of Fenton Hill with the ring-fracture zone approximately three miles east of the project area. The project area is covered by a thick ash-flow tuff, and other minor, volcanic units before reaching the sedimentary and metamorphic sequence of rocks that overlies the Precambrian igneous and metamorphic complex.

Volcanic and Sedimentary Units [Surface to 733 m (2405 ft)]

The shallow 733 m (2405 ft) volcanic and sedimentary units encountered in the four Fenton Hill HDR holes are as follows (Figure 2).

Bandelier Tuff (Quaternary)

Depth m (Ft)	Description
0-12 (0-40)	Soft, light gray-brown volcanic ash. Welded tuff with inclusions of angular quartz and a trace of sanidine.
12-15 (40-50)	Dirty reddish clay with embedded quartz fragments and tuff.

Paliza Canyon (Tertiary)

15-17 (50-55)	Loose sand composed of coarse angular to sub-rounded quartz grains and crystals, plus a small amount of tuff and basaltic gravel.
17-21 (55-70)	Coarse basaltic gravel. Weathered. Possibly large boulders. Also some loose quartz fragments and latite pebbles.
21-26 (70-85)	Same as above, with approximately 60% loose, rounded, medium-grained sand.
26-43 (85-142)	Medium-grained, rounded quartz sand. Dirty, and slightly reddish with clay.
43-47 (142-155)	Friable tuffaceous sandstone to loose sand. Increasing amounts of light brown, translucent tightly cemented sandstone.

Depth m (Ft)	Description
47-58 (155-190)	Light brown, fine-to medium-grained, rounded to sub-angular sandstone. This grades from extremely siliceous to hard but friable.
58-107 (190-350)	Coarse weathered gravel. Pebbles and boulders of andesitic basalt, latite, etc. Contains inclusions of hornblende, biotite, and other dark minerals. A small percentage of quartz and chalcedony. Becomes reddish below 70 m (230 ft).
107-119 (350-390)	Coarse light gray volcanic gravel. latite or dacite. Inclusions of biotite, hornblende, quartz, etc. Possibly a flow breccia. This contains the volcanic aquifer.

Abiquiu Tuff (Tertiary)

119-140 (390-460)	white to light brown, tuffaceous, slightly clayey sand. Medium-grained, loosely consolidated, rounded to subrounded. Mostly quartz.

Abo (Permian)

140-381 (460-1250)	The volcanics are resting unconformably upon the eroded surface of the Abo red beds. These continental deposits consist largely of dark red shales, with smaller amounts of dark gray and black platy shales. The sandstones are fairly coarse-grained, angular to rounded, red, gray, and white. The interbedded limestones are sandy and silty to clean and finely crystalline, and range from gray and brown to white. Two prominent sand bodies occur from 305-320 m (1000-1050 ft) and from 341-354 m (1120-1160 ft). The upper of these, probably an aquifer, is a loose to slightly consolidated, coarse, rounded to subrounded, clean quartz sand. It is possibly a beach sand or river gravel, and was so permeable in EE-2 that 60 barrels of mud were lost. The lower sand is almost identical with the upper sand, but slightly tighter and cemented with calcareous material. No fluid has been lost in the lower sand.

Madera Limestone & Sandia Formation (Pennslyvanian & Mississippian)

Depth m (ft)	Description
381-411 (1250-1350)	Dense, light-colored limestone, finely crystalline to chalky. Thin beds of clastic material, ranging from gummy gray shale to fine gray silts and sands. Upper portion tends to be fossiliferous, with abundant bryozoans and fusalinids.
411-472 (1350-1550)	Silty to shaly, gray to light brown limestone. Thin beds of fine-grained, light gray, calcareous sandstone 442-454 m (1450-1490 ft).
472-509 (1550-1670)	Dense, finely crystalline to sub-litholographic brown limestone. Bottom 9 m (30 ft) of this interval is a clastic zone in GT-2 and EE-3, possibly arkosic.
509-585 (1670-1920)	Dense, light colored, finely crystalline to chalky limestone. Light gray, silty shale 512-530 m (1680-1740 ft) and 564-573 m (1850-1880 ft). A few thin beds of fine-grained, rounded, friable, calcareous sandstone, possibly arkosic in GT-2. Bottom 9 m (30 ft) is a very hard, white, siliceous, slightly pyritic limestone.
585-733 (1920-2405)	The samples in this interval are either extremely poor and heavily contaminated with lost circulation material, or else completely nonexistent because of lost returns. Based on the rate of penetration and the lost circulation, it is assumed to be a cavernous limestone. Bits are pulled from the hole with the teeth filled with a gummy gray shale and clay containing rounded nodules of dense, very finely crystalline brown limestone. This clay and the embedded nodules are probably laid down secondarily on the floors of the caves. This section also includes a few clastic zones. A core cut in GT-2 from 685-688 m (2248-2258 ft) recovered nothing but a handful of loose, rounded gravel, mostly smaller than 0.64 cm (1/4 in). And the 9 m (30 ft) immediately overlying the eroded Precambrian surface at 733 m (2405 ft) appears to be a granite wash.

Precambrian Igneous and Metamorphic Complex [from 733 m (2400 ft)]

The Precambrian crystalline rocks that underlie the Fenton Hill site range in age from 1.3 to 1.7 billion years. This complex geological terrain is composed of six basic rock types (Table 1).

(1) Syenogranitic to monzonogranitic gneisses and intrusives
(2) Granodioritic gneisses
(3) Granodioritic intrusives
(4) Tonalitic gneisses
(5) Mafic-rich schists and amphibolites
(6) Hydrothermally altered metamorphic and igneous rocks

The Phase I reservoir (GT-2B and EE-1) was developed in a relatively homogeneous rock type (Fig. 3). However the Phase II reservoir (EE-2 and EE-3) encompasses both igneous and metamorphic rock types with a wide range of compositions (Table 2). Locally the metamorphic and igneous lithologies may have been deformed. Several faults may possibly cut through the deeper reservoir.

OPTIMIZED CASING PROGRAM TO MINIMIZE HOLE STABILITY PROBLEMS

A significant reduction in hole problems associated with severe loss circulation zones has been accomplished by the prudent selection of casing points (Fig. 3 and Table 3). Severe problems were encountered in GT-2B and EE-1 from sloughing of the Abo and Madera Formations. The worst sloughing occurred when cavernous areas in the Sandia and Madera Limestones were encountered. Loss of hydrostatic head caused sloughing of shales within the Abo and Madera Formations.

Two specific severe loss circulation zones encountered in the sedimentary sections were: (1) at ±579 m (±1900 ft) in the Madera Formation and (2) at ±716 m (±2350 ft) in the Sandia Formation. Both occurred within limestone lithologies. After drilling the first two wells (GT-2B and EE-1), it became apparent that the casing program should be adapted to minimize the amount of open hole when each of the loss zones was encountered. Thus, on EE-2 the surface casing (20 in.) was set to 543 m (1780 ft) to avoid leaving the sloughing shales exposed when the loss zones were penetrated. However, this left approximately 182 m (600 ft) of open hole exposed when the large cavernous zone of the Sandia Formation was encountered. Setting another string of casing to the top of that loss zone was prohibited by constraints of casing design. As a result, intermediate casing was set into only the upper section 15-61 m (50-200 ft) of the Precambrian crystalline rocks. Thus, effects of the loss zones were lowered but not eliminated by the careful selection of a casing program.

GENERAL MUD PROGRAM

The upper volcanic and sedimentary formations were drilled utilizing a bentonite based drilling fluid. Because of the large hole sizes (26 in. and 17-1/2 in.) an inverted rheology was selected to provide adequate hole cleaning. The inverted rheology (YP >PV) was maintained by using a polymeric flocculant and reducing the use of deflocculants. Filtration reducing agents used on GT-2B and EE-1 maintained a filtrate of 6-10 cc API. It was felt that this reduction in static filtration rate would help stabilize the mud making shales of the Abo Formation, but no filtrate reducing agents were used in EE-2 or EE-3 and no appreciable increase in problems associated with the Abo Formation was noticed by this omission. These problems included not only mud making characteristics, but also severe and immediate hole-instability problems unless adequate hydrostatic pressure was maintained upon the formation.

Lost circulation proved to be the most costly problem associated with the upper sedimentary and volcanic formations. Slight losses of returns that occurred in fractured portions of the volcanic tuff [surface to 137 m (450 ft)] could be quickly healed with conventional fibrous bridging agents such as cottonseed hulls, cedar fiber, and aspen fiber. In contrast, severe loss of circulation did occur within the cavernous limestone portion of the Pennsylvanian Sandia and Madera Formations. This loss of returns resulted in a drastic loss of hydrostatic head [fluid level 274-518 m (900-1700 ft)] leaving no fluid upon portions of the unstable Abo Formation. Directly resulting from this problem was stuck pipe (EE-1), repetitive reaming of large sections [±396 m (±1300 ft)] of the borehole on all four wells, poor casing cement jobs, and in EE-2 a damaged intermediate casing string (13-3/8 in.).

The remaining depth of the holes was drilled in a Precambrian metamorphic and igneous complex. Problems with this portion of the holes were extreme abrasiveness, extreme temperatures 320°C (608°F) BHT, and some areas of apparent instability. Due to the deviated nature of the holes (35° from vertical), and the fact that water was used as the primary circulating fluid, a combination of the large circulating volume used and the abrasiveness of metamorphic and igneous rocks caused special torque-reduction problems. The best lubricating agent tried was a mixture of triglycerides and alcohols. The effects of the lubricant was temporary at high temperatures [>191°C (>375°F)] and therefore, the lubricant had to be constantly replenished. Furthermore extremely high torque and drag placed a high priority on minimizing drill pipe failure due to corrosion. Corrosion inhibition was complicated by high temperatures and the circulation of high volumes (15,000 bbls) of water to provide an adequate cooling surface. An oxygen scavanger (ammonium bisulfite) and maintenance of a basic pH, successfully moderated this corrosion problem.

Areas of apparent rock instability occur within the Precambrian crystalline rocks. Water-sensitive clays (smectites) were found in some zones within the deep crystalline rocks. This clay may be a hydrothermal alteration product formed along faults and shear zones. Occasionally tight-hole problems encountered while drilling EE-2 were most likely a result of these clays. No remedial action was taken because of the relative infrequent occurrence, and unpredictable position of the clays.

SPECIFIC LOSS ZONES WITHIN SEDIMENTARY AND VOLCANIC UNITS

The upper volcanic formations (Bandelier Tuff, Paliza Canyon and Abiquiu Tuff) pose some bothersome but not severe problems in loss of circulation. The upper sections of the Bandelier Tuff in particular are moderately fractured and some mud was lost to these fracture. Considerable loss of mud to fractures within this tuff occurred in GT-2B and EE-1. After the drilling of EE-1 the conductor pipe (30 in.) was set to a depth of 27 m (88 ft) in EE-2 which effectively eliminated loss of mud to near surface fractures.

Loss of circulation in the Abo Formation has also been minimal. In earlier wells drilled at Fenton Hill (GT-2B and EE-1) almost no loss occurred, but later wells (EE-2 and EE-3) did experience slight losses (175 and 200 bbls) into this formation at 316 m (1037 ft) and 165 m (540 ft). Both zones were quickly healed with fibrous bridging agents. Lenses of red clay within the Abo Formation caused a considerable increase in viscosity of the drilling fluid (usually a 40 to 60 point rise in funnel viscosity) when hydrated. The most economical method to control viscosity and mud weight is simple dilution if adequate water and reserve pit space is on hand, but would be uneconomical if a low filtrate was necessary and expensive filtrate control agents are added. Our experience showed that addition of filtrate reduction compounds was not cost effective. Such agents were added on wells GT-2B and EE-1, but were omitted on EE-2 and EE-3. The omission resulted in no apparent difference in the problems associated with hole sloughing of the Abo Formation on EE-2 or EE-3.

By far the most troublesome and severe loss of circulation occurred in the cavernous limestone portions of the Madera and Sandia Formations. Drill holes encountered in the cavernous Sandia ±716 m (±2350 ft) ranged from 1-4.9 m (3-16 ft) in height. Two loss zones required considerable time, effort and money to overcome urgent and continuing problems. The loss zone within the Madera Formation was variable in severity. For example, in GT-2B all attempts at regaining circulation were unsuccessful. They included heavy use of bridging agents (1,500 bbls of 30% by volume of lost circulation material), three separate 50 bbl high filtrate squeezes, and numerous cementation efforts which used up a total of 2700 sacks. The complete loss of returns reduced the hydrostatic head substantially and with this loss, severe sloughing of the Abo Formation and portions of the Madera Formation shales occurred. This required repetitive reaming (16 days) before the sloughing shales could be successfully cased off. Similar, but not as severe losses occurred in subsequent wells (EE-1 and EE-2). EE-1 lost 600 bbls of mud to this zone, but returns were gained by using large amounts of fibrous bridging agents. Drilling mud for EE-2 was pretreated with 30% by volume fibrous bridging materials. Only 35 bbls were lost. On EE-3 a 1 m (3 ft) cavern was encountered at 576 m (1890 ft). The resultant sloughing of the Abo and Madera Formations was almost identical to that in GT-2B. Finally casing was set at 482 m (1580 ft) to seal off the Abo and upper Madera loss zones.

The cavernous portion of the Sandia Formation is located ±15 m (±50 ft) above the contact with the basement complex rocks (Fig. 2). All four wells encountered this cavernous limestone and no remedial efforts attempted succeeded in regaining circulation. It would have been advantageous to restore circulation because of the sloughing problems encountered in the Abo and Madera Formations up holes.

Several different techniques were used in attempts to restore circulation in the Sandia Formation. The use of air mist and the use of a "gel" foam were tried without success in GT-2B. Both restored circulation temporarily, but neither exerted enough hydrostatic pressure to prevent the sloughing of the exposed shale sections. This sloughing caused repetitive reaming, large volumes of fill on trips and the sticking of the drill string. Attempts to bridge the cavern with lost circulation material (15,700 bbls with up to 60% by volume lost circulation material), gunk squeezes (300 bbls) and a massive cementation effort (a total of ±12,000 sacks on all four wells) all proved futile (Table 4). The plan finally adopted was to minimize the amount of open hole exposed by utilizing a carefully designed casing program when the cavern was first encountered. As soon as full returns were lost, the plan was to drill without returns into the basement complex and then set intermediate casing. This program was adopted on EE-2 and EE-3. The casing program in both wells was to run 20 in. surface casing near the top of the first troublesome loss zone at ±579 m (±1900 ft) and then drill through both loss zones without returns as rapidly as possible and then into the basement complex rocks. Thirteen and three-eights casing was then set into the basement complex. In both wells this intermediate casing string (13-3/8 in.) was set only after considerable reaming and washing through bridges and fill. During the running of the EE-2 casing and drilling after casing, the casing became damaged in several places. In the latter portions of the drilling operations the casing collapsed and a lengthy fishing job resulted (approximately 120 days and a cost of approximately $2.5 million). At this time no totally problem-free method has been devised to overcome the loss of circulation and subsequent problems involved with this cavernous section.

One possible method of alleviating the lost circulation problem is to avoid it entirely by drilling through the trouble zones with cable tools. The following is a suggested hole size and casing program for this option:

Hole Size cm (in.)	Depth m (ft)	Casing cm (in.)	Remarks
91.4 (36)	183 (600)	71.1 (28)*	mudded
68.6 (27)	305-384(1000-1260)	61 (24)*	mudded
58.4 (23)	716 (2350)	50.8 (20)*	cemented
If necessary		45.7 (18) liner	cemented
44.1 (17-3/8)	792 (2600)	34 (13-3/8)	cemented

The mudded casing may be removed from the hole after subsequent casing is run, or underreamed and lowered as conditions dictate. A modified Bucyrus-Erie 48-L drilling unit is capable of handling this option, and should cost less than half of what a comparable rotary unit would.

DRILLING FLUID PROBLEMS IN THE PRECAMBRIAN CRYSTALLINE ROCKS

The igneous and metamorphic complex rocks of the Precambrian basement are characterized by hard, abrasive rocks with localized areas of incompetence. The drilling fluid program used during this interval was designed to alleviate two potential problems:

- Corrosion control to minimize drill pipe failure and
- Drill string lubrication to minimize torque and drag.

Water was selected as a circulating fluid because of extreme downhole temperatures 320°C (608°F) BHT, the initial apparent competency of the basement complex rock, and its relative inexpensiveness.

Corrosion control took on added significance because of the excessive torque and drag that developed as a result of directional drilling. A large reserve pond (1-1/2 - 2 acres) was provided to cool the water as it exited from the borehole. The large surface area not only cooled the water, but, adversely, allowed for ample surface exchange of oxygen. Therefore water pumped downhole would be entrained with large concentrations of oxygen. Large quantities of oxygen scavanger (ammonium bisulfite) were added to the water prior to pumping downhole to remove the oxygen dissolved in the water. A basic pH (9.5 to 10.5) was maintained to further reduce corrosion and

*These casing sizes are not standard, but are available in collarless, flush joints. They are often used in cable tool operations to facilitate driving the casing deeper after underreaming.

scaling was controlled by the use of a phosphonate compound which removed the cations available for precipitate formation. Results were monitored by corrosion coupons (Table 5), which revealed that whenever the above treatments were followed, corrosion was kept to a minimum.

Lubrication of the drill string became important at greater depths due to excessive torque and drag. The drill string was routinely subjected to the upper limits of stress recommended by API tables as a result of directional drilling in the basement complex rocks. The frequent drill pipe failures that were a direct consequence of these problems have resulted in extremely costly fishing operations ($850,000.00 on EE-3). Several methods of lubrication were evaluated and used. The use of granular objects such as walnut hulls or teflon beads, to reduce torque, were eliminated because of their inability to suspend in clear water and also because of possible bridging effects in fracturing operations. An oil base drilling fluid was also eliminated because of the high cost of such fluids and the fact that Fenton Hill lies within an area of environmental sensitivity. A biodegradable, soluble chemical added to the water was therefore selected as the best possibility for providing acceptable torque and drag reduction.

An additional limitation was placed upon the lubricating agent due to the high downhole temperatures. Several soluble chemicals were tested in the laboratory but only two were found suitable to test downhole (Table 6). The best additive was a conventional agent that consisted of modified triglycerides and alcohols. The effects of the lubricant were found to be only temporary in the hotter bottom-hole sections of the string. Therefore the lubricant had to be constantly replenished while drilling. This was accomplished by batchwise additions of the chemical. The addition of this chemical additive succeeded in reducing excessive wear to the drill string and surface equipment. It also allowed more weight to be placed on the cutting surface of the bit rather than the side of the borehole.

Found within the igneous and metamorphic sections were regions of incompetence as reflected by loss of circulation and borehole instability. One particular loss of circulation occurred on EE-3 at 3042 m (9980 ft). The zone was bridged using walnut hulls and mica flakes (two materials that do not degrade rapidly under conditions of extreme heat and pressure). However the zone periodically reopened and had to be again bridged with these materials. Additional areas of instability were found throughout the basement complex section (EE-2) from 3170-4206 m (10,400-13,800 ft). It appears that this region contains large percentages of smectite clays that swell and slough upon contact with drilling fluid. The sloughing of the clay and rock fragments imbedded within or adjacent to the clay created drag and sticking problems during the drilling of EE-2. It is currently thought that these clays are probably the result of the hydrothermal alteration in cataclastic zones of igneous and metamorphic rocks and may eventually produce problems during the production phase of EE-2 and EE-3.

CONCLUSIONS

The HDR project is unique in its method of energy production but it is not unique among geothermal projects in that a substantial amount of time and money have been spent in attempts to cure severe loss of circulation during the exploration phase of development. At Fenton Hill several types of fibrous bridging agents achieved little success in the severe loss zones. Various types of cements ranging from basic class H cement to thixotropic cement to diatomaceous earth have been tried at considerable expense but with only limited success. A total of approximately 2% of exploratory funds at Fenton Hill have been spent on loss circulation materials (Table 7) in an attempt to solve these problems.

An adequate solution to this type of severe loss of circulation should center on intensive research not only in the area of new types of cementing material but also on new types of cementing tools and also new drillable sleeves that can be firmly set through severe loss zones. Loss circulation problems will probably always be associated with geothermal operations due to the geological terrain that contain near-surface geothermal potential. This problem is relatively new to geothermal (especially the HDR program) exploration and development projects within the United States but has been a continuous problem with geothermal development in other countries. Research and development in the area of loss circulation problems is vitally needed so that geothermal exploration and development can be more cost effective.

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TABLE 1

Chemical and mineralogic characteristics of the Precambrian rocks encountered at Fenton Hill. The symbol "$\bar{x}$" is the mean, "S_x" is the standard deviation, and "( )" is the number of analyses used in the tabulation (after Laney and Laughlin, 1980).

	SYENOGRANITIC TO MONZOGRANITIC	GRANODIORITIC		GRANODIORITIC (INTRUSIVE)		TONALITIC		MAFIC - RICH ROCKS[2]		ALTERED ZONES
	GT-2	GT-2	EE-2	GT-2	EE-2	GT-2	EE-2	GT-2	EE-2	EE-2
Weight % SiO_2	$\bar{x}$ = 75.0 S_x = 1.1 (10)	$\bar{x}$ = 68.7 S_x = 2.5 (7)	$\bar{x}$ = 66.6 S_x = 0.1 (2)	$\bar{x}$ = 64.3 S_x = 1.4 (6)	$\bar{x}$ = 68.1 S_x = 2.8 (5)	$\bar{x}$ = 68.3 S_x = 3.0 (3)	$\bar{x}$ = 63.3 S_x = 5.4 (2)	$\bar{x}$ = 55.1 S_x = 0.0 (2)	$\bar{x}$ = 59.7 S_x = 0.3 (2)	$\bar{x}$ = 52.3 S_x = 6.2 (2)
Volume % Quartz	$\bar{x}$ = 35.6 S_x = 5.3 (15)	$\bar{x}$ = 33.7 S_x = 6.1 (15)	$\bar{x}$ = 33.2 S_x = 4.0 (4)	$\bar{x}$ = 25.7 S_x = 3.1 (3)	$\bar{x}$ = 26.1 S_x = 4.4 (8)	$\bar{x}$ = 28.0 S_x = 6.5 (4)	$\bar{x}$ = 22.7 S_x = 5.6 (5)	$\bar{x}$ = 10.0 S_x = 6.1 (3)	$\bar{x}$ = 9.2 S_x = 2.1 (3)	? $\lesssim$ 10.0
Volume % Quartz + K-spar	$\bar{x}$ = 69.0 S_x = 5.8 (15)	$\bar{x}$ = 45.4 S_x = 7.1 (15)	$\bar{x}$ = 44.5 S_x = 5.5 (4)	$\bar{x}$ = 44.3 S_x = 5.1 (3)	$\bar{x}$ = 48.6 S_x = 12.5 (8)	$\bar{x}$ = 28.4 S_x = 6.6 (4)	$\bar{x}$ = 22.8 S_x = 5.8 (5)	$\bar{x}$ = 10.3 S_x = 5.8 (3)	$\bar{x}$ = 12.3 S_x = 1.7 (3)	? Variable, low
[1]Volume % Mafics	$\bar{x}$ = 4.3 S_x = 2.1 (15)	$\bar{x}$ = 13.7 S_x = 6.0 (15)	$\bar{x}$ = 24.6 S_x = 5.3 (4)	$\bar{x}$ = 19.5 S_x = 2.1 (3)	$\bar{x}$ = 19.0 S_x = 7.1 (8)	$\bar{x}$ = 21.0 S_x = 5.1 (4)	$\bar{x}$ = 38.2 S_x = 10.3 (5)	$\bar{x}$ = 45.9 S_x = 4.9 (3)	$\bar{x}$ = 64.7 S_x = 6.0 (3)	? Dominated by clay type minerals

[1] Includes biotite, muscovite chlorite, amphibole, opaques, epidote, apatite, sphene, zircon, and allanite.

[2] Includes metavolcanic rocks, biotite-chlorite schists and amphibolites.

Table 2

Comparison of the compositions of the Phase I and Phase II reservoirs at Fenton Hill (after Laney and Laughlin, 1980)

Rock Type	Phase I Reservoir GT-2, EE-1 2621 to 2957 m (8600 to 9700 ft)	Phase II Reservoir EE-2, EE-3 (Tentatively 3200 to 4420 m TVD or 1433 m (4700 ft) along the EE-2 deviated borehole)
Syenogranitic to Monzogranitic	--	8.0%
Granodioritic	10.0%	49.0%
Granodioritic (intrusive)	90.0%	8.0%
Tonalitic	--	15.0%
Mafic-Rich Rocks	--	14.0%
Altered Zones	--	6.0%
Summary	100% Granodioritic	57% Granodioritic 35% Tonalitic to Mafic (includes altered rock) 8% Granitic

Table 3

Casing Programs for GT-2B, EE-1, EE-2, and EE-3 at Fenton Hill

Well	Conductor Casing m (ft)	Surface Casing m (ft)	Intermediate Casing m (ft)	Deep Casing m (ft)	Production Casing m (ft)	Total Depth m (ft)
GT-2	Surface-20 (65) (20 in.)	Surface-488 (1600) (13-3/8 in.)	Surface-773 (2535) (10-3/4 in.)	-	Surface-2612 (8570) (7-5/8 in.)	2932 (9619)[a]
EE-1	Surface-3 (10) (30 in.)	Surface-177 (580) (20 in.)	Surface-741 (2431) (13-3/8 in.)	Surface-1957 (6420) (10-3/4 in.)	Surface-304 (999) (7-5/8 in.) 304-2926 (999-9599) (8-5/8 in.)	3064 (10,053)[b]
EE-2	Surface-25 (82) (28-1/2 in.)	Surface-544 (1783) (20 in.)	Surface-790 (2593) (13-3/8 in.)	-	Surface-3528 (11,576) (9-5/8 in.)	4660 (15,289)
EE-3	Surface-30 (100) (30 in.)	Surface-482 (1580) (20 in.)	Surface-778 (2554) (13-3/8 in.)	-	Surface-3200 (10,500)[c] (9-5/8 in.)	4420 (14,200)[d]

[a] Drilled in three phases:
Phase I Surface to 1937 m (6356 ft)
Phase II 1937 to 2042 m (6356 to 6701 ft)
Phase III 2042 to 2932 m (6701 to 9619 ft)

[b] Drilled in two phases:
Phase I Surface to 2099 m (6886 ft)
Phase II 2099 to 3064 m (6886 to 10,053 ft)

[c] Casing had not been run at the time of this paper

[d] Projected total depth of 4420 m (14,500 ft)

Table 4

Lost Circulation Material Volumes

	GT-2B	EE-1	EE-2	EE-3	TOTAL
CEMENT (sks)	3,000	500	5,000	3,500	12,000
LCM (bbl)	1,600	8,300	3,500	2,300	15,700

Table 5

Corrosion Rates on Drill Pipe

Well Name and No.	n	Range (lbs/sq ft/yr)	$\bar{X} + S_x$ (lbs/sq ft/yr)
G-2	-	no record	
EE-1	15	0.005 to 1.81	0.618 $\pm$ 0.578
EE-2	33	0.01 to 5.10	1.33 $\pm$ 1.17
EE-3 (to date 11/22)	14	0.10 to 2.11	0.72 $\pm$ 0.648

Table 6

Drillstring Torque and Drag Reduction Lubricating Agents

Product/Conc.	Torque (amps) Before	After	Duration
2 ppb oil base lubricant	600	450	30 mins.
1 ppb oil base lubricant plus 1 ppb triglycerides & alcohol	600	500	1 hour
2 ppb triglycerides & alcohol	600	400	2 hours
20 ppb bentonite	600	550	30 mins.

Table 7

Cost of Lost Circulation Materials at Fenton Hill

	Direct Costs			
	LCM	Air Mist	Cement	Total
GT-2B	$16,000.00	$3,000.00	$50,000.00	$69,000.00
EE-1	$56,000.00	-	$12,000.00	$68,000.00
EE-2	$63,000.00	-	$74,000.00	$137,000.00
EE-3	$40,000.00	-	$62,000.00	$102,000.00
TOTAL	$175,000.00		$198,000.00	$316,000.00

GRAND TOTAL COST FOR ALL LOST CIRCULATION MATERIALS: $316,000.00

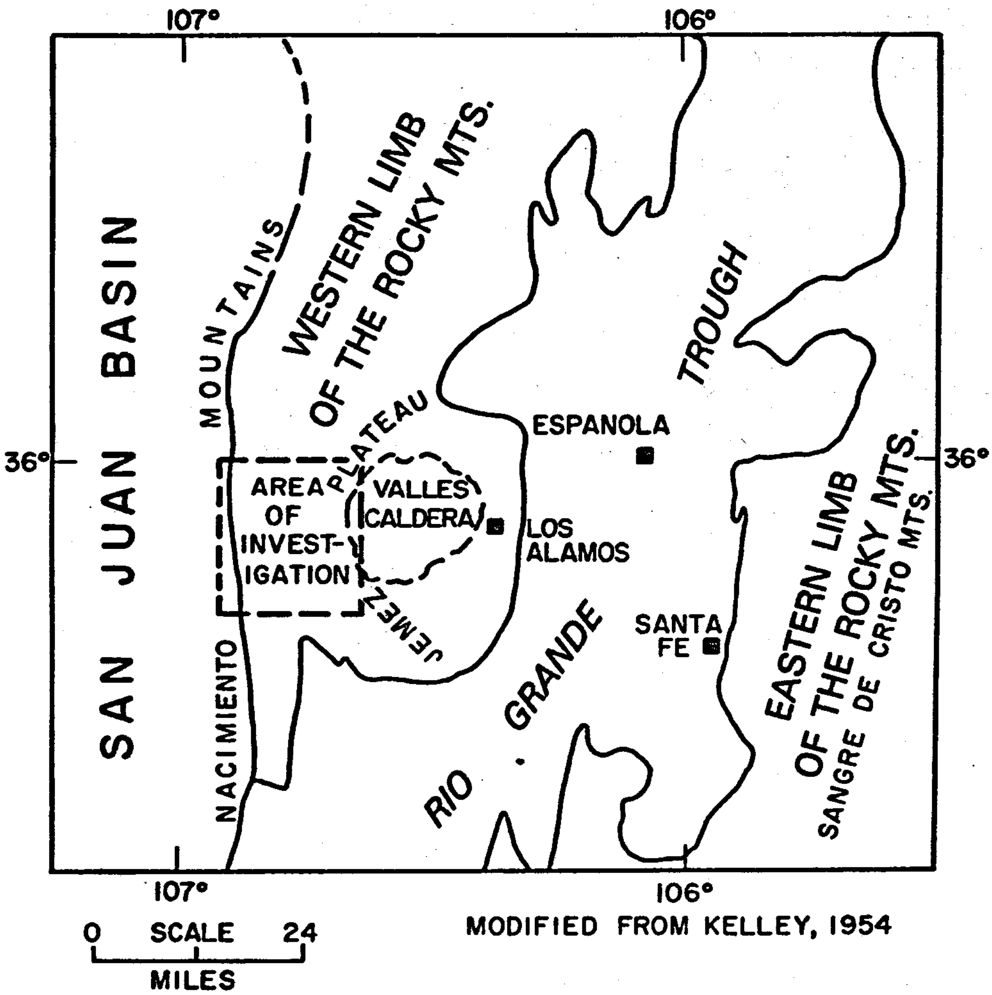

Figure 1. Major Structural Features and Area of Investigation in North-central New Mexico.

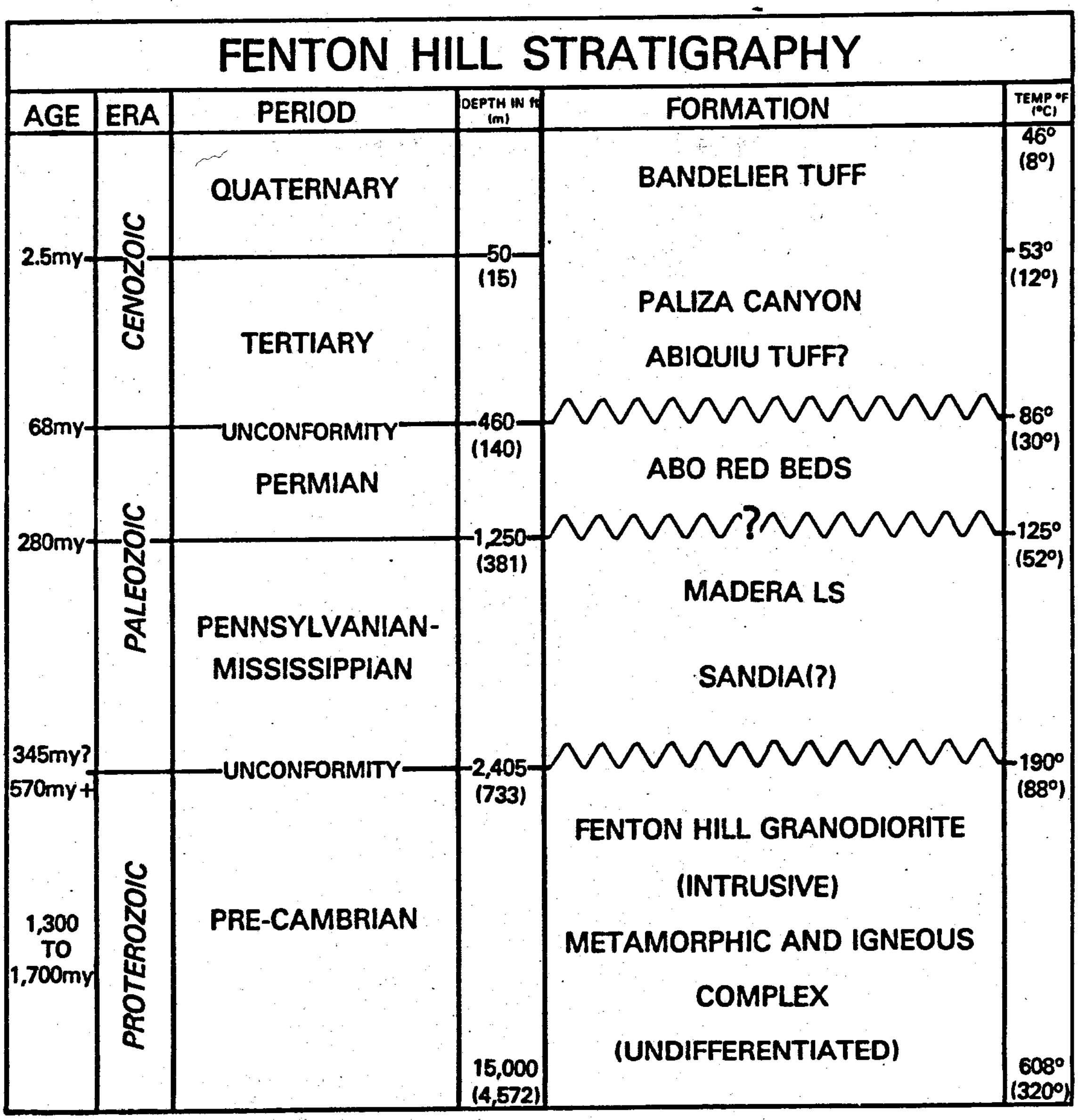

Figure 2. Geologic Column of Fenton Hill Stratigraphy.

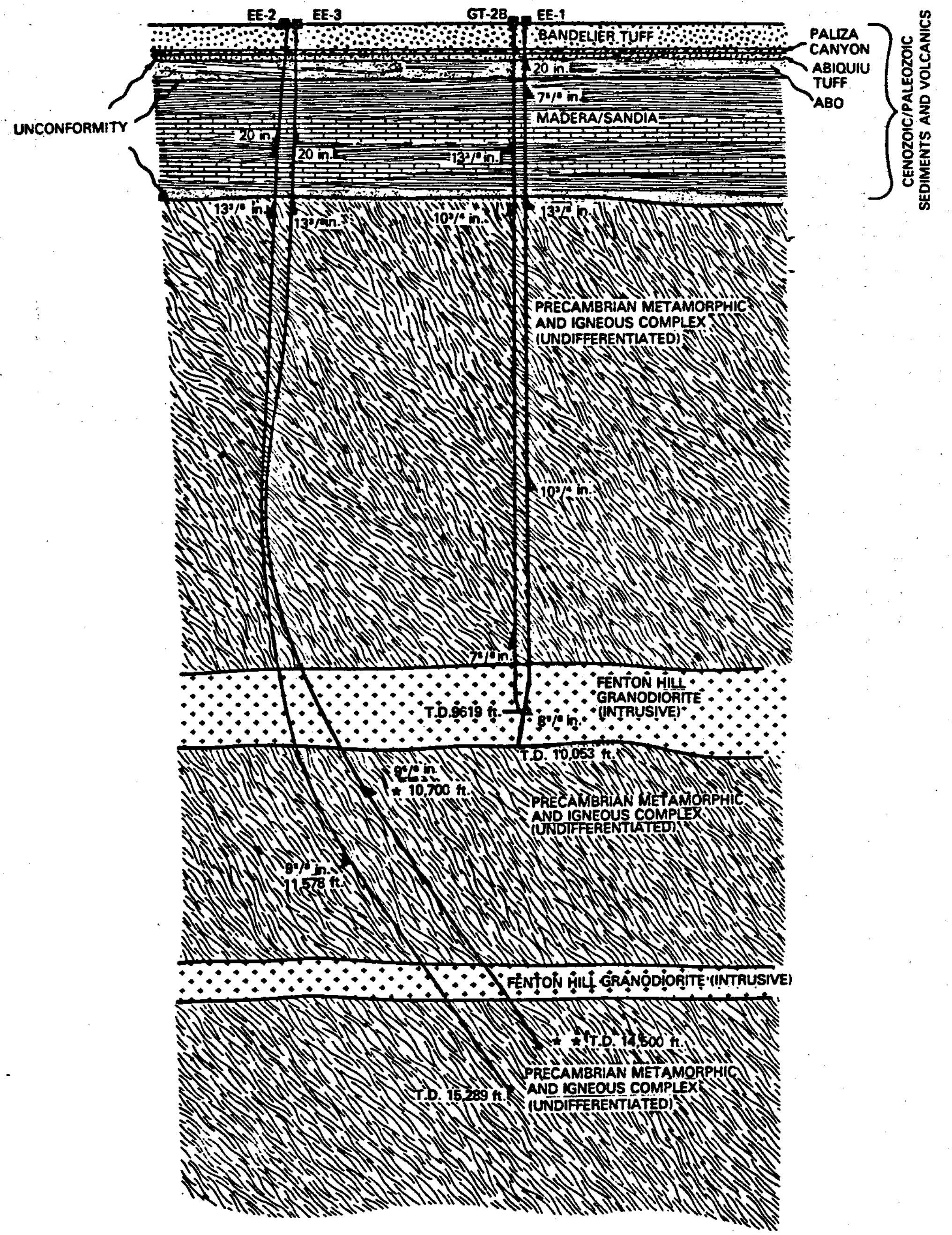

Figure 3. Geologic Formations, Lithologics, and Casing Program for the Fenton Hill HDR project. See Table 3 for details of casing program.